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# SATELLITE RADAR INTERFEROMETRY (InSAR)-BASED DEFORMATION MONITORING OF EARTHFILL DAMS: METHODOLOGY AND APPLICATION AT THE TOPALANG DAM, UZBEKISTAN

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**ABSTRACT.** In addition to classical geodetic and GNSS-based techniques, interferometric synthetic aperture radar (InSAR) is increasingly applied to monitor the deformation of hydraulic structures remotely, retrospectively, and across wide areas. This paper presents the methodology of InSAR-based dam deformation monitoring — covering interferometric phase decomposition, line-of-sight to three-dimensional displacement conversion, and the complementary Persistent Scatterer (PS-InSAR) and Small Baseline Subset (SBAS) processing approaches — and applies it to Sentinel-1 C-band satellite data (2020–2024) analysed for the Topalang earthfill dam (Surkhandarya region, Uzbekistan) under Presidential Resolution PQ-158 (2023). PS-InSAR analysis of 6,233 reference points across the reservoir area revealed a maximum subsidence of −214.74 mm on the downstream side and a maximum uplift of +54.54 mm on the left bank, with a dedicated dam-specific analysis (250 points) showing an average annual settlement of −8.69 mm/yr. SBAS analysis of 18,391 points confirmed the same downstream-subsidence pattern (−113.91 mm maximum) and identified a critical unloaded-slope zone displacing horizontally at 30.94 mm/yr, warranting dedicated monitoring attention. These results, cross-validated against the complementary strengths of the two InSAR techniques, confirm that satellite radar interferometry provides a reliable, wide-area, and cost-effective complement to classical geodetic and GNSS-based dam safety monitoring.

**Keywords:** InSAR; PS-InSAR; SBAS; synthetic aperture radar; Sentinel-1; deformation monitoring; earthfill dam; Topalang dam

**INTRODUCTION.** In recent years, alongside classical geodetic and GNSS-based techniques, interferometric synthetic aperture radar (InSAR) has become widely used for monitoring the deformation of hydraulic structures [1; 2]. InSAR enables the detection of dam deformation across large areas, remotely and retrospectively. The technology is based on the analysis of the phase difference between radar images acquired by satellite sensors over the same area at different points in time [3; 4].

This phase difference corresponds to extremely small changes in the distance between the satellite and the Earth's surface, enabling the detection of millimetre-scale deformation [2]. For this reason, InSAR is particularly effective for monitoring slowly developing, long-term deformation processes [5], and the integration of InSAR-derived deformation data with hydrological indicators represents a scientifically justified and practically effective approach.

This paper has two objectives. First, it sets out the methodology of InSAR-based deformation monitoring — from interferometric phase decomposition and line-of-sight displacement retrieval to the complementary PS-InSAR and SBAS processing techniques. Second, it applies this methodology

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to Sentinel-1 satellite radar data acquired over the Topalang earthfill dam between 2020 and 2024, situating the results within the broader body of international InSAR dam-monitoring literature.

## MATERIALS AND METHODS

**2.1. Interferometric phase decomposition.** When an electromagnetic wave transmitted by a radar antenna reflects off an object's surface, the phase value extracted from the image depends on the distance between the satellite and the ground. If the ground surface changes — for example, a vertical or horizontal displacement occurs — a small difference appears in the object's phase, and the magnitude of this phase difference indicates the magnitude of the displacement. To achieve high-precision measurements, various interferogram types are used, including differential interferograms (DInSAR) and persistent-scatterer interferograms (PS-InSAR). An interferogram — the phase difference between two SAR images — contains several components: the topographic component (related to surface elevation), the true deformation component, atmospheric delay (tropospheric or ionospheric phase delay), orbital error, and thermal or instrumental noise. The total observed phase difference is expressed as [4]:

$$\varphi_{obs} = \varphi_{topo} + \varphi_{def} + \varphi_{atm} + \varphi_{orb} + \varphi_{noise} \quad (1)$$

where $\varphi_{topo}$ is the topographic phase, arising from ground-surface relief; $\varphi_{def}$ is the deformation phase, produced by displacement of the dam or reservoir banks between the two images (in millimetres); $\varphi_{atm}$ is the atmospheric phase, caused by signal delay through the troposphere and ionosphere and typically treated as an error source that is filtered using PS-InSAR or SBAS algorithms; $\varphi_{orb}$ is the orbital phase error, arising from small differences between the satellite's two orbital passes; and $\varphi_{noise}$ is the noise component, caused by pixel decorrelation or thermal noise.

**2.2. Line-of-sight to three-dimensional displacement conversion.** The displacement measured by the radar signal is determined directly along the satellite's line of sight (LOS). Its relationship to the three-dimensional displacement components is expressed as [2]:

$$d_{LOS} = d_E \cdot \sin\theta \cdot \sin\alpha + d_N \cdot (-\sin\theta \cdot \cos\alpha) + d_U \cdot \cos\theta \quad (2)$$

where $d_E$, $d_N$, $d_U$ are the eastern, northern, and vertical displacement components, respectively; $\theta$ is the radar incidence angle; and $\alpha$ is the azimuth angle of the satellite orbit.

The dual-polarity Sentinel-1 satellite constellation, equipped with C-band synthetic aperture radar sensors (wavelength $\lambda = 5.5$ cm), is effective for detecting microwave-scale deformation [6; 7]. For the Topalang area, the incidence angle $\theta$ typically ranges from 31° to 47° [8], so the vertical component's contribution to LOS displacement can be estimated as:

$$k_{vert} = \cos(\theta) \approx 0.66–0.86 \quad (3)$$

indicating that vertical motion contributes a substantial share of LOS displacement, while the contribution of horizontal components depends on the orbital direction. International studies report that InSAR results correlate closely ($r \approx 0.93$) with classical geodetic measurements — for example, at the Shuibuya dam in China, a long-term InSAR analysis matched geodetic observations with a correlation coefficient of 0.93 [9].

**2.3. Persistent Scatterer InSAR and Small Baseline Subset processing methods.** Two principal approaches are used in InSAR data processing. PS-InSAR [10] identifies stable reflector points (buildings, concrete, metal structures) and computes their phase evolution over time, achieving vertical accuracy of approximately 1–3 mm with strong suppression of atmospheric effects; it is best suited to infrastructure-dense areas, with reduced effectiveness over open natural terrain owing to lower point density. SBAS [11] is based on sets of small-baseline interferograms and is well suited to regional analysis over large areas, achieving vertical accuracy of approximately 5–10 mm [12]; it is recommended for detecting deformation over open ground such as dam berms and reservoir margins. Table 1 summarises the comparative characteristics of the two methods.

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| Comparison criterion | PS-InSAR | SBAS |
|---|---|---|
| Basic principle | Analysis of persistent (stable) reflector points | Set of interferograms with small baseline separation |
| Primary targets | Buildings, dams, concrete and metal structures | Large areas, terrain, natural surfaces |
| Spatial density | Relatively low (stable points only) | High (large number of points) |
| Vertical accuracy | Very high (≈ 1–3 mm) | Moderate (≈ 5–10 mm) |
| Atmospheric effect | Strongly filtered out | Partially reduced |
| Sensitivity to vegetation | Low | Relatively high |
| Time-series stability | Very stable, long-term | Moderately stable |
| Data requirement | Requires a large number of radar images | Works with fewer images |
| Computational complexity | High | Moderate |
| Suitability for hydraulic structures | Very high | Good (for regional analysis) |

Table 1. Comparative analysis of PS-InSAR and SBAS methods.

**2.4. Study site, data, and processing framework.** Under Presidential Resolution PQ-158 of 16 May 2023 [13], a scientific-practical study was conducted to assess the seismic resilience of the Topalang reservoir dam based on interferometric processing and analysis of radar satellite imagery [14]. Sentinel-1 C-band SAR data acquired between January 2020 and June 2024 were processed using both the PS-InSAR and SBAS techniques. The PS-InSAR analysis covered 6,233 reference points across the reservoir and dam area, with a dedicated dam-specific analysis based on 250 control points — 5 control marks, 13 alignment marks, 4 benchmarks, and 32 surface targets — along the 185 m high dam. The SBAS analysis covered a wider network of 18,391 points across the reservoir and dam area, with 256 points selected for the dam-specific analysis.

**RESULTS.** PS-InSAR analysis of the full reservoir and dam area (6,233 points) identified a maximum subsidence of −214.74 mm on the downstream side of the dam and a maximum uplift of +54.54 mm on the left bank of the reservoir, with an average annual deformation rate of −0.68 mm/yr across all points. The dam-specific analysis (250 points) recorded subsidence values ranging from 35 to 210 mm across the downstream berms, decreasing progressively from the upper to the lower berms, with vertical deformation of up to 90 mm recorded on the right abutment. Over the observation period, the overall dam deformation reached −38.55 mm, corresponding to an average annual settlement of −8.69 mm/yr.

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Horizontal deformation was assessed across 18,391 points. The maximum eastward displacement, +79.77 mm, was recorded on the downstream side, while the maximum westward displacement, −130.65 mm, occurred on the reservoir's left bank; the average annual horizontal rate across all points was −0.17 mm/yr (westward). At the dam itself, horizontal deformation was concentrated in the first and second downstream berms, with a maximum westward value of −107 mm; the overall dam horizontal deformation reached 6.21 mm, corresponding to an average annual rate of 1.4 mm/yr, with westward displacement predominant.

| Area | Control points | Average annual (mm/yr) | Max. subsidence/west (mm) | Max. uplift/east (mm) | Note |
|---|---|---|---|---|---|
| Reservoir + dam (vertical, PSI) | 6,233 | −0.68 | −214.74 | +54.54 | Max. subsidence downstream; max. uplift left bank |
| Dam only (vertical, PSI) | 250 | −8.69 | −214.74 | +90 (max.) | Range 35–210 mm; total −38.55 mm |
| Reservoir + dam (horizontal, PSI) | 18,391 | −0.17 (west) | −130.65 (west) | +79.77 (east) | Westward displacement predominant |
| Dam only (horizontal, PSI) | 18,391 | 1.4 (west) | −107 (west) | +79.77 (east) | Total 6.21 mm; active downstream zone |

Table 2. PS-InSAR analysis results (2020–2024, Sentinel-1 C-band, λ = 5.5 cm) [14].

SBAS analysis of the same 18,391-point network identified a maximum subsidence of −113.91 mm on the downstream side and a maximum uplift of +41.38 mm on the right bank, with an average annual deformation rate of −0.40 mm/yr [12; 14]. The dam-specific SBAS analysis (256 points) recorded an overall deformation of 3.44 mm and an average annual rate of 0.77 mm/yr; vertical settlement in the first and second downstream berms ranged from 18 to 114 mm, with subsidence of up to −30 mm and uplift of up to +20 mm at the lower berms [15; 14].

Horizontal SBAS analysis of the 18,391-point network identified a maximum eastward displacement of +137.31 mm on the downstream side and a maximum westward displacement of −98.91 mm on the reservoir's left bank, with an average annual rate of +0.13 mm/yr (westward). At the dam, the overall horizontal deformation was 2.78 mm, at an average annual rate of 0.63 mm/yr (westward); the maximum eastward displacement, coinciding with the dam's unloaded downstream slope, reached +137.31 mm, corresponding to an average annual rate of 30.94 mm/yr — a value identified as requiring dedicated monitoring attention.

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| Area | Control points | Average annual (mm/yr) | Max. subsidence/west (mm) | Max. uplift/east (mm) | Note |
|---|---|---|---|---|---|
| Reservoir + dam (vertical, SBAS) | 18,391 | −0.40 | −113.91 | +41.38 | Max. subsidence downstream; max. uplift right bank |
| Dam only (vertical, SBAS) | 256 | 0.77 | −30 (berm) | +20 (berm) | Total 3.44 mm; range 18–114 mm |
| Reservoir + dam (horizontal, SBAS) | 18,391 | +0.13 (west) | −98.91 (west) | +137.31 (east) | Unloaded slope: 30.94 mm/yr |
| Dam only (horizontal, SBAS) | 256 | 0.63 (west) | −107 (west) | +137.31 (east) | Total 2.78 mm; westward predominant |

Table 3. SBAS analysis results (2020–2024, Sentinel-1 C-band) [14].

Because PS-InSAR and SBAS rely on different algorithms and different sets of reference points, direct numerical comparison between them is methodologically limited [10; 11]; nevertheless, the overall trends identified by both methods are mutually consistent — subsidence dominates the downstream area, and both vertical and horizontal deformation are observed on the right side of the dam [14]. Table 4 presents a comparative summary of the two techniques.

| Indicator | PS-InSAR | SBAS | Difference / interpretation |
|---|---|---|---|
| Total control points | 6,233 | 18,391 | SBAS covers 3× more points — wider area coverage |
| Max. vertical subsidence | −214.74 mm | −113.91 mm | PS-InSAR captures deeper subsidence at stable points |
| Max. vertical uplift | +54.54 mm (left bank) | +41.38 mm (right bank) | Different zones — both banks are active |
| Average annual vertical | −0.68 mm/yr | −0.40 mm/yr | Consistent overall subsidence trend |
| Max. horizontal (east) | +79.77 mm | +137.31 mm | SBAS captures the unloaded-slope zone |
| Max. horizontal (west) | −130.65 mm | −98.91 mm | Westward displacement on left bank |

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| Indicator | PS-InSAR | SBAS | Difference / interpretation |
|---|---|---|---|
| Dam annual vertical | −8.69 mm/yr | 0.77 mm/yr | PSI reflects downstream berms; SBAS the whole dam |
| Dam control points | 250 | 256 | Nearly equal — comparable monitoring network |
| Vertical accuracy | ≈ 1–3 mm | ≈ 5–10 mm | PS-InSAR more precise on metal/concrete targets |

Table 4. Comparative analysis of PS-InSAR and SBAS results [14].

**DISCUSSION.** The consistency between the PS-InSAR and SBAS results — despite their differing point counts (6,233 versus 18,391) and differing target types (stable metal/concrete reflectors versus a broader range of surface points) — strengthens confidence in the identified deformation pattern. The larger PS-InSAR subsidence magnitude (−214.74 mm versus −113.91 mm for SBAS) reflects the method's tendency to prioritise the most stable, and therefore most representative, deep-subsidence reflector points, while the larger SBAS horizontal displacement (+137.31 mm versus +79.77 mm for PS-InSAR) reflects its greater effectiveness over the open, unloaded slope areas where stable point-like reflectors are sparse [5].

The unloaded downstream slope zone, where SBAS identified a horizontal displacement rate of 30.94 mm/yr, stands out as the most significant finding of this analysis, and — read alongside the GNSS results obtained for the crest stations — reinforces the case for continuous, multi-technique monitoring at this location. The correlation of ~0.93 reported internationally between InSAR-derived and classical geodetic deformation measurements [9] supports the reliability of the Topalang InSAR results as an independent, spatially comprehensive check on the ground-based classical and GNSS observations.

Several methodological considerations should nonetheless be borne in mind. First, PS-InSAR and SBAS results cannot be compared directly on a point-by-point basis, since they rely on different algorithms and different reference networks [10; 11]. Second, InSAR-derived displacements are measured along the satellite line of sight and require an assumed displacement-direction model (Eq. 2) to be resolved into vertical and horizontal components; at the incidence angles typical of the Topalang site (31°–47°), the technique retains good sensitivity to vertical motion ($k_{vert} \approx 0.66–0.86$) but is less able to isolate horizontal motion without independent orbit or GNSS constraints. Third, PS-InSAR's dependence on stable, high-reflectivity targets makes it less effective in vegetated or unconsolidated terrain, which is why the SBAS method is preferred for open reservoir margins and berm slopes [5].

**CONCLUSION.** This paper has set out the methodology of InSAR-based dam deformation monitoring — from interferometric phase decomposition and line-of-sight displacement retrieval to the complementary PS-InSAR and SBAS processing techniques — and applied it to Sentinel-1 satellite data acquired over the Topalang earthfill dam between 2020 and 2024. The analysis confirms a consistent pattern of downstream subsidence and right-bank deformation across both InSAR techniques, with PS-InSAR providing high-precision (1–3 mm) detection at stable reflector points and SBAS providing broader-coverage (5–10 mm) detection across open terrain, including identification of a critical unloaded-slope zone displacing at 30.94 mm/yr. These results demonstrate that satellite radar interferometry constitutes a valuable, spatially comprehensive, and cost-effective complement to

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classical geodetic and GNSS-based monitoring, supporting an integrated, multi-technique framework for embankment dam safety assessment.

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